THE NEBULAR SHOCK WAVE MODEL FOR CHONDRULE FORMATION: SIMULATIONS AND COMPARISONS WITH METEORITIC CONSTRAINTS. L. L. Hood, Lunar and Planetary Lab, University of Arizona, Tucson AZ 85721.

Previous work has indicated that gas dynamic shock waves occurring within a relatively cool (<650 K), dusty (>1–10 mm-sized particles per m^3) nebular environment can potentially provide the transient, multiple heating events needed to form chondrules and other formerly molten inclusions in chondrites [1,2,3]. Possible mechanisms for generation of time-dependent gas dynamic shocks in the protoplanetary accretion disk include (i) gravitational instabilities and density waves in a massive disk during the early infall stage [4] or during FU Orionis episodes [5]; (ii) inhomogeneous disk accretion, e.g., collisions of infalling clumps of gas and dust with the surface of the accretion disk [6]; and (iii) bow shocks upstream of forming planetesimals perturbed into eccentric orbits. Here, we report improved numerical simulations and analytical calculations to allow more detailed comparisons with meteoritic constraints.

Because of their relatively small dimensions, planetesimal bow shocks would not easily bring a mm-sized particle to a fully molten state although this mechanism may be important for formation of secondary igneous and/or sintered rims [3]. During the early infall stage and during FU Orionis episodes when the disk is massive and the accretion rate is large, ambient midplane disk temperatures near 2–3 a.u. are likely to exceed 1000 K [5] so chondrule formation during these periods is problematical. However, these episodes may provide a reasonable setting for the formation of refractory inclusions (CAIs) [7]. For the simulations reported here, we assume a low-mass, relatively cool nebula with parameters given in ref. 3. Large-scale shocks are generated by disturbances at the surface of the nebula and propagate toward the midplane. The source of these disturbances is assumed to be collisions of infalling clumps of circumstellar gas and dust [6]. Two specific cases are considered. In the first case, the required gas clumps are assumed to consist of shocks embedded in the accretion flow from the surrounding molecular cloud core. In the second case, the gas clumps are assumed to consist of matter ejected from the near vicinity of the protosun. Figure 1 shows an example of one simulation of the second case.

Particle Heating and Cooling Calculations: In order to determine the gas density, temperature, and velocity structure immediately behind the shock front, the effects of post-shock radiative cooling must be included [8]. For this purpose, we have found that an isothermal shock with a linear transition region is a reasonable approximation that agrees with more detailed numerical simulations [8]. Recent calculations [9] for 1 mm radius olivine spheres yield emissivities of less than 0.1 for temperatures in the range 10^3–10^4 K. These emissivities are significantly less than have been assumed in previous gas dynamic chondrule formation heating simulations. The net consequence for a given dust particle is an increase in heating rate (and maximum temperature attained) due to reduced radiative losses. We have carried out numerical integrations of the gas-grain energy and momentum transfer equations for single particles to determine the extent to which the above modifications affect earlier estimates of particle heating times. Results indicate that shocks with Mach numbers exceeding 5 are capable of bringing mm-sized silicate particles to melting temperatures in times of order minutes or less as required by meteoritic constraints. The cooling time of a molten silicate particle depends on both the post-shock gas dynamic heating rate and on the net rate of radiative energy loss. Neglecting the former, simulations for the case of a one-dimensional, optically thick dust cloud indicate that radiative cooling times of the order of hours are possible.

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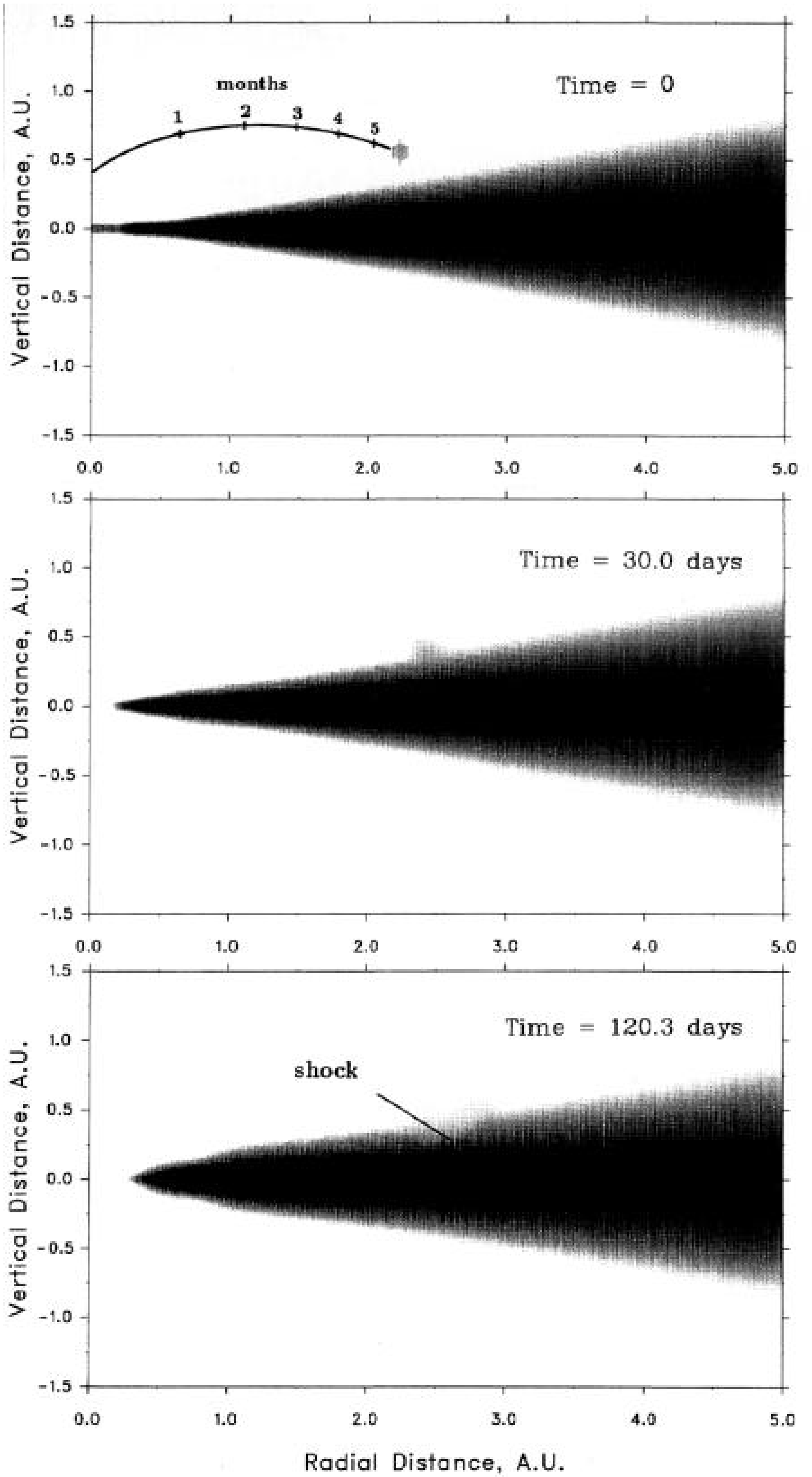
Time = 0
months
1
2
3
4
5
Time = 30.0 days
Time = 120.3 days
shock
Vertical Distance, A.U.
Radial Distance, A.U.
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.0
1.0
2.0
3.0
4.0
5.0

Fig. 1.